Optics Communications 390 (2017) 16–21

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Characteristics and performance of a two-lens slit spatial filter for high power lasers

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A R T I C L E I N F O

Keywords:
Spatial filtering
Image relay
Laser

A B S T R A C T

The characteristics of a two-lens slit spatial filtering system on image relay and spatial filtering are discussed with detailed theoretical calculation and numerical simulation. The slit spatial filter can be used as the cavity spatial filter in large laser systems, such as National Ignition Facility, which can significantly decrease the focal intensity in cavity spatial filter and suppress or even avoid the pinhole (slit) closure while keeping the output power and beam quality. Additionally, the overall length of the cavity spatial filter can be greatly reduced with the use of the two-lens slit spatial filter.

1. Introduction

Laser beams will inevitably encounter modulations of spatial frequencies when propagating in optical paths, resulting in small-scale self-focusing and degrading the beam quality [1,2], especially in inertial confinement fusion lasers that have higher intensities. Spatial Filter (SF) [3] is the conventional and effective equipment to clean off the rapidly growing spatial frequencies [4–6], which consists of two convex lenses and a pinhole placed at their common focus. Nonetheless, the pinhole aperture should be less than a specific size to be able to efficiently clean off the rapidly growing spatial frequencies, thus the pinhole aperture in large laser systems has to bear higher intense laser irradiation [7,8], which may induce pinhole closure [9,10]. Besides, the SFs in large laser systems have to be placed in high vacuum [11–13] to avoid breakdown in air. To lower the focal intensities and postpone pinhole closure time, the focal lengths of the lenses in SFs have to be long enough. Although there are several generations of SFs in improving pinhole aperture in the past decades such as [14], these problems have not been efficiently solved, which not only limit the load capacity and raise the cost of high power lasers but also give rise to difficulty in collimation and maintenance of the lasers.

In order to solve the above problems, the conventional pinhole SF has to be improved. By introducing cylindrical lenses into SFs, the laser beams can be focused into a line instead of the original spot, thus the focal area can be significantly enlarged and the focal intensity greatly lowered. Moreover, the pinhole aperture used for spatial filtering is replaced with two orthogonal slit apertures. In this way, the conventional pinhole SF is converted into a slit SF. In 2012, A. C. Erlandson in Lawrence Livermore National Laboratory (LLNL) proposed a slit SF [15], in which four cylindrical lenses are used to replace the two original spherical lenses in pinhole SF. The four-lens slit SF is useful in enlarging the focal area, but it will raise cost and is difficult to collimate and maintain. In our previous work [16], we proposed a new kind of slit SF with the combination of two cylindrical lenses and a spherical lens in 2014, which has a better filtering performance and a simpler structure. However, the above four- or three-lens slit SFs are far more complicated than the conventional pinhole SF. For practical applications of the slit SF, the configuration should be further simplified, say a similar configuration to that of the conventional SF and easy to replace the traditional filter. A kind of slit SF with two astigmatic lenses has been mentioned in [15,17], but there are no relevant descriptions on its characteristics. In this paper, the characteristics of the two-lens slit SF on image relay and spatial filtering are discussed with theoretical calculation and numerical simulation. Besides, this new-type slit SF is used to simulate National Ignition Facility (NIF) system, and better performances are obtained compared to the original Cavity Spatial Filter (CSF) in NIF system.

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http://dx.doi.org/10.1016/j.optcom.2016.12.038
Received 24 August 2016; Received in revised form 17 November 2016; Accepted 16 December 2016

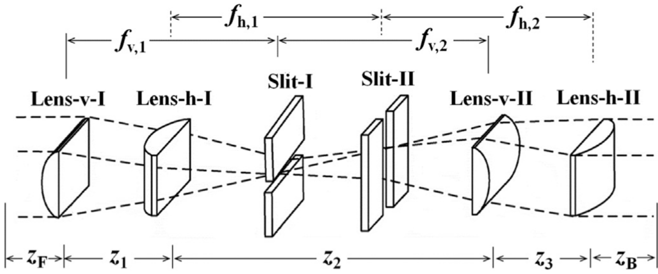

Fig. 1. Schematic diagram of the four-lens slit SF.

2. Theory of the two-lens slit SF

Since the two-lens slit SF is a particular case of the four-lens slit SF for which the distances between both cylindrical lenses on the left and on the right are reduced to zero, the four-lens slit SF is studied at first for a general case. The configuration of the four-lens slit SF is shown in Fig. 1, which includes four lenses and two orthogonal slit apertures placed in front of and after the common focal planes. The focal length of the first and the second vertical (y-direction) lenses, the first and the second horizontal (x-direction) lenses are $f_{v,1}$ and $f_{v,2}$, $f_{h,1}$ and $f_{h,2}$, respectively. There is $f_{h,2}=N_h \cdot f_{h,1}$ and $f_{v,2}=N_v \cdot f_{v,1}$, where N_v is the vertical magnification of beam aperture and N_h is the horizontal magnification.

Due to the differences between the left two lenses in focal length and position (so is the right two lenses), the positions of the front (and back) focal planes in y- and x-directions will be apart from each other. In order to understand the image relay function of slit SF, an incident plane in front of lens-v-I by a distance of z_F is chosen, and an output plane is behind lens-h-II by a distance of z_B. For the convenience of calculation, the original super-Gaussian beam incident on slit SF is replaced here by a multi-Gaussian beam [18–20]:

$$U_i(x,y)=\frac{\sum_{m=-R}^{R}\exp\left[-\frac{(x-mW)^2}{W^2}\right]\sum_{n=-R}^{R}\exp\left[-\frac{(y-nW)^2}{W^2}\right]}{\sum_{m=-R}^{R}\exp(-m^2)\sum_{n=-R}^{R}\exp(-n^2)} \quad (1)$$

where R is the order of multi-Gaussian function, W is the waist radius of each Gaussian component in multi-Gaussian function. According to Rayleigh-Sommerfeld diffraction integral and lens transformation theory [21], the output laser beam can be obtained:

$$U_o(x,y)=\exp(ikS)\frac{\sum_{m=-R}^{R}\exp\left[-ik\frac{(x/N_h+mW)^2}{ikW^2-2z_F-2z_1+2f_{h,1}+2f_{h,1}/N_h-2z_B/N_h^2}\right]}{\sqrt{\frac{N_h(ikW^2-2z_F-2z_1+2f_{h,1})+2f_{h,1}-2z_B/N_h}{ikW^2}}\sum_{m=-R}^{R}\exp(-m^2)} \times\frac{\sum_{n=-R}^{R}\exp\left[-ik\frac{(y/N_v+nW)^2}{ikW^2-2z_F+2f_{v,1}+2f_{v,1}/N_v-2z_B/N_v^2-2z_3/N_v^2}\right]}{\sqrt{\frac{N_v(ikW^2-2z_F+2f_{v,1})+2f_{v,1}-2z_B/N_v-2z_3/N_v}{ikW^2}}\sum_{n=-R}^{R}\exp(-n^2)} \quad (2)$$

where S is the whole optical path of the slit SF system, and k is wave number. To illustrate the image relay of the SF, the output beam function should be close to the incident one, thus two conditions are acquired according to Eq. (1) and Eq. (2):

$$z_F+z_B/N_h^2=f_{h,1}+f_{h,1}/N_h-z_1 \quad (3)$$

$$z_F+z_B/N_v^2=f_{v,1}+f_{v,1}/N_v-z_3/N_v^2 \quad (4)$$

With the two conditions in Eq. (3) and Eq. (4), the output laser beam function in Eq. (2) can be rewritten as:

$$U_o(x,y)=\frac{\sum_{m=-R}^{R}\exp\left[-\frac{(x/N_h+mW)^2}{W^2}\right]\sum_{n=-R}^{R}\exp\left[-\frac{(y/N_v+nW)^2}{W^2}\right]}{\sqrt{N_hN_v}\sum_{m=-R}^{R}\exp(-m^2)\sum_{n=-R}^{R}\exp(-n^2)} \quad (5)$$

When vertical and horizontal magnifications are both unity, the form of Eq. (5) is similar to that of Eq. (1). Since the range of x and y are symmetrical with respect to the coordinate origin, it takes no effect on Eq. (5). If the magnifications are not unity, the distribution of laser beam will increase by N_h and N_v times in x- and y-directions, and the intensity of output beam will decrease by $N_h \cdot N_v$ times while beam area will increase by $N_h \cdot N_v$ times, which coincides with the optical transmission principle that the product of intensity and beam area is a constant.

If setting z_2 as zero and N_h being equal to N_v, the configuration in Fig. 1 could become a three-lens slit SF. According to Eq. (3) and Eq. (4), f_{h1} will become equal to f_{v2} leading to the combination of the cylindrical Lens-h-I and Lens-v-II into a spherical lens, and both z_F and z_B will become zero, which agree with the results in [16]. For more structural convenience, two-lens slit SF could be obtained if setting z_1 and z_3 as zero as shown in Fig. 2, which includes two lenses and two orthogonal slit apertures placed in front of and after the common focal planes. The vertical and the horizontal focal lengths of lens-I and lens-II are $f_{v,1}$ and $f_{h,1}$, $f_{v,2}$ and $f_{h,2}$, respectively. The focal length difference g is the difference between the vertical and the horizontal focal lengths of each lens. N_v should be different with N_h, or the slit SF will become a conventional pinhole SF.

According to Eq. (3) and Eq. (4), the incident distance z_F and the output distance z_B of the two-lens slit SF can be obtained:

$$z_F=f_{h,1}\frac{N_h+1}{N_h+N_v} \quad (6)$$

$$z_B=f_{h,2}\frac{N_v(N_h+1)}{N_h+N_v} \quad (7)$$

where z_F and z_B are the focal plane positions of the slit SF system. For convenience, the vertical magnification in this paper is always considered larger than the horizontal magnification ($f_{h,1}=f_{v,1}+g$), thus the relationships between the vertical and the horizontal magnifications can be obtained:

$$N_v=(N_hf_{h,1}+g)/(f_{h,1}-g) \quad (8)$$

Additionally, the form of Eq. (6) and Eq. (7) can be simplified if the horizontal magnification N_h is equal to 1, as shown below:

$$z_F=f_{h,1}-g \quad (9)$$

$$z_B=f_{h,1}+g \quad (10)$$

If the vertical magnification N_v is equal to 1, then the form of Eq. (6) and Eq. (7) can be simplified as:

$$z_F=f_{h,1} \quad (11)$$

$$z_B=f_{h,2} \quad (12)$$

It can be seen from Eq. (9) and Eq. (12) that the z_F and z_B are different from each other.

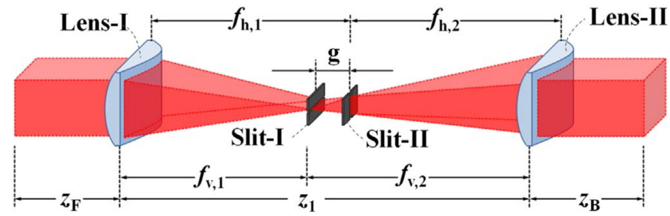

Fig. 2. Schematic diagram of the two-lens slit SF.

3. Numerical analysis of the two-lens slit SF

Since the huge calculating works for large aperture, we choose an 8th-order super-Gaussian square beam with the aperture of 10 mm×10 mm to illustrate the image relay process and evaluate the filtering characteristics of the two-lens slit SF. To show the image relay, there is no filter aperture in SFs. The incident beam is modulated by a